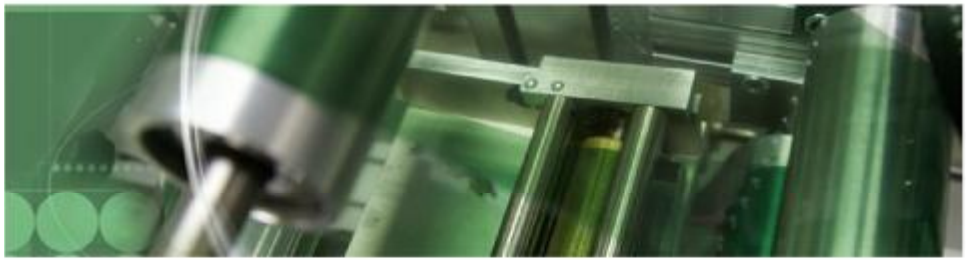


INTELLIGENT PRINTING FUN MAT FUNCTIONAL MATERIALS

# Future of Paper as Substrate for Printed Electronics and Sensors

Martti Toivakka
Laboratory of Paper Coating and Converting
Center for Functional Materials
Åbo Akademi University

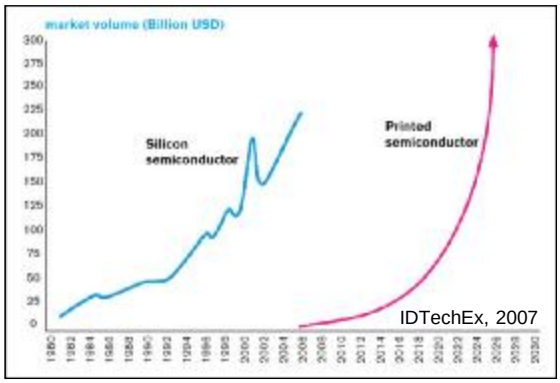

Fulton Innovation

# Paper Electronics = Printed Electronics on Paper




# Market Prediction for Printed Electronics

- IDTechEx, April 19, 2012:
  - › "...printed electronics is expected to reach $45 billion in 2022..." (2011 market size = $2.2 Billion)
- electronics.ca, April 11, 2012:
  - › "Global Market for Printed Electronics to Reach $12.6 Billion in 2016"
- NanoMarkets report, 2010:
  - › Thin film/printable batteries market to reach $5.6 Billion by 2015
  - › Printed sensors generate $5.4 billion in revenues by 2016



# Market Prediction for Printed Electronics

...but recently also:

NanoMarkets

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**Time for a Dose of Market Realism in "Printed Electronics"**

**Published:** March 01, 2010 **Category:**

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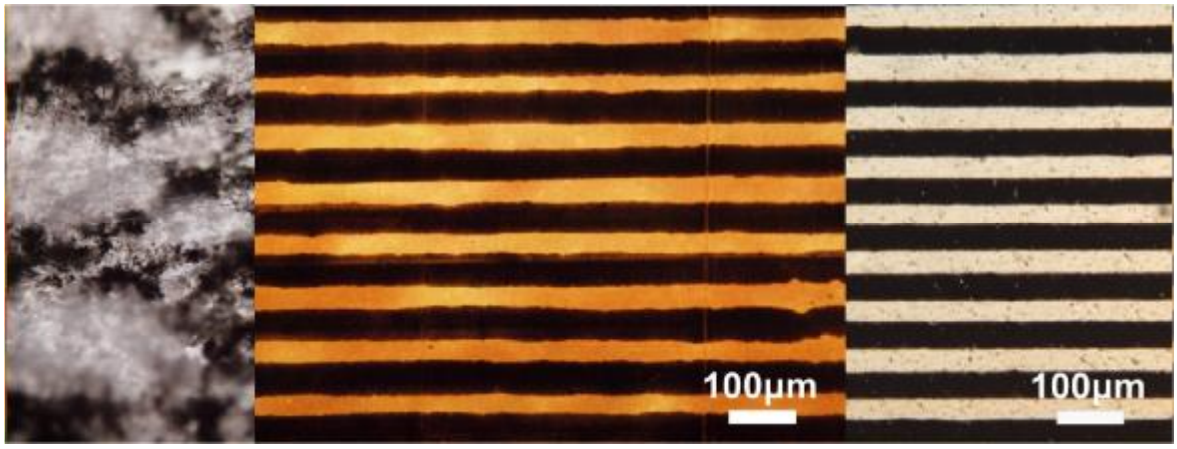
Let's face it, printed electronics hasn't turned out the way we all hoped. Just a few years ago the market was talking itself into a frenzy--sharing fantasies of those majestic R2R fabs churning out organic RFID tags and display backplanes with the speed of the New York Times coming off the presses. Seems rather silly in retrospect.



# Printing Electronics on Paper

Recyclable paper for printed electronics:
Mineral pigment and latex barrier coatings
Calendered to RMS roughness: <100 nm

[*Org. Electron.* 10 (2009) 1020]



# Printability of Functional Inks on Paper

- Printability determined by compatibility of ink – printing method – substrate

- Inks (solution processable functional materials):
  - Conductive particulate inks, e.g. nanoparticle/micron-size silver, carbon, gold, copper...
  - Conductive polymer inks, e.g. PEDOT:PSS, PANI...
  - Semiconducting inks, e.g. P3HT, PQT...
  - Insulators, e.g. PVP, PMMA...
- Printing / coating method:
  - Inkjet, flexography, rotogravure, screen printing...
  - Reverse gravure, spray, slot, curtain...
- Substrate: Paper or board, i.e. natural fiber-based substrate



# Making Paper Compatible with Printed Electronics

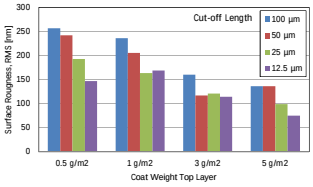
- We need to measure and control surface properties of the substrate: roughness, (surface) porosity, wettability, chemical activity/inertness, barrier properties, mechanical properties, dimensional stability, humidity

- Surface treatment methods to improve printability:
  - Existing:
    - surface sizing
    - pigment coating
    - dispersion coating
    - extrusion coating
    - corona treatment
  - Novel methods:
    - plasma activation/coating
    - nanoparticle deposition
    - sol-gel coating
    - atomic layer deposition
    - chemical vapor deposition

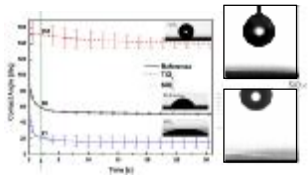
# The Ink Behavior on a Substrate is Controlled by (in Addition to Ink and Printer properties):

- Barrier properties (permeability)


- Surface roughness



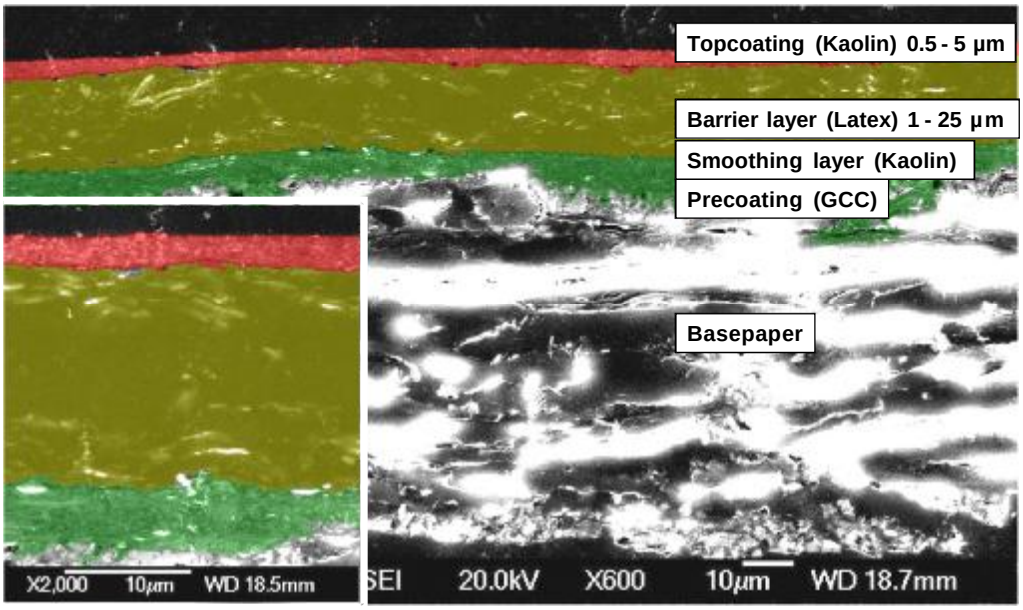

- Surface energy



- <u>(Surface) porosity and pore volume</u>

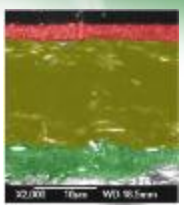


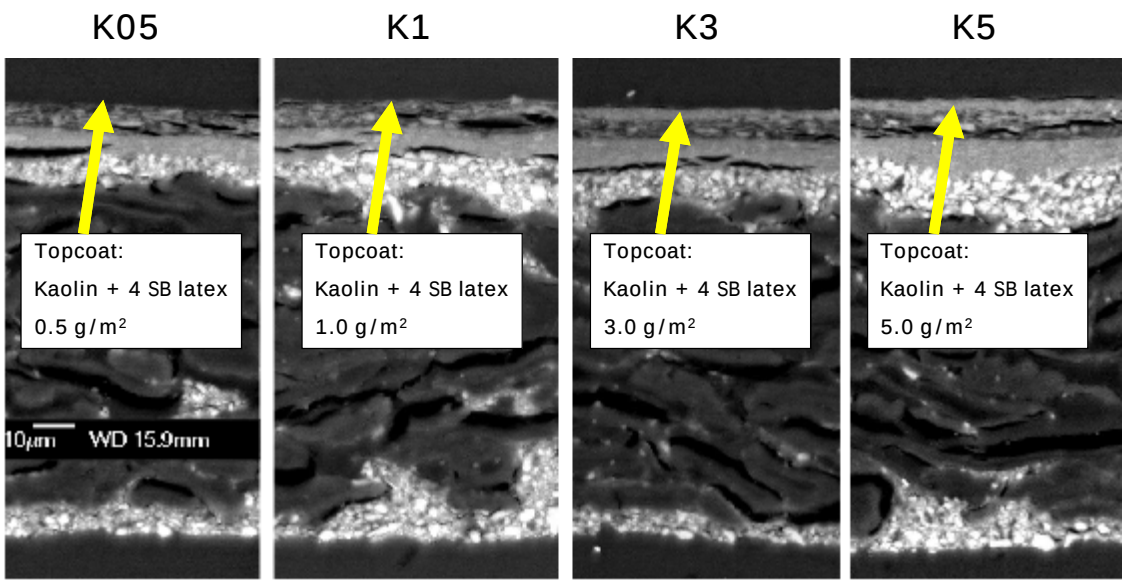
# Example Substrate Concept For Paper Electronics




Bollström, R., A. Määttänen, D. Tobjörk, P. Ihalainen, N. Kaihovirta, R. Österbacka, J. Peltonen, and M. Toivakka. "A multilayer coated fiber-based substrate suitable for printed functionality." *Organic Electronics* 10, no. 5 (2009): 1020–1023.

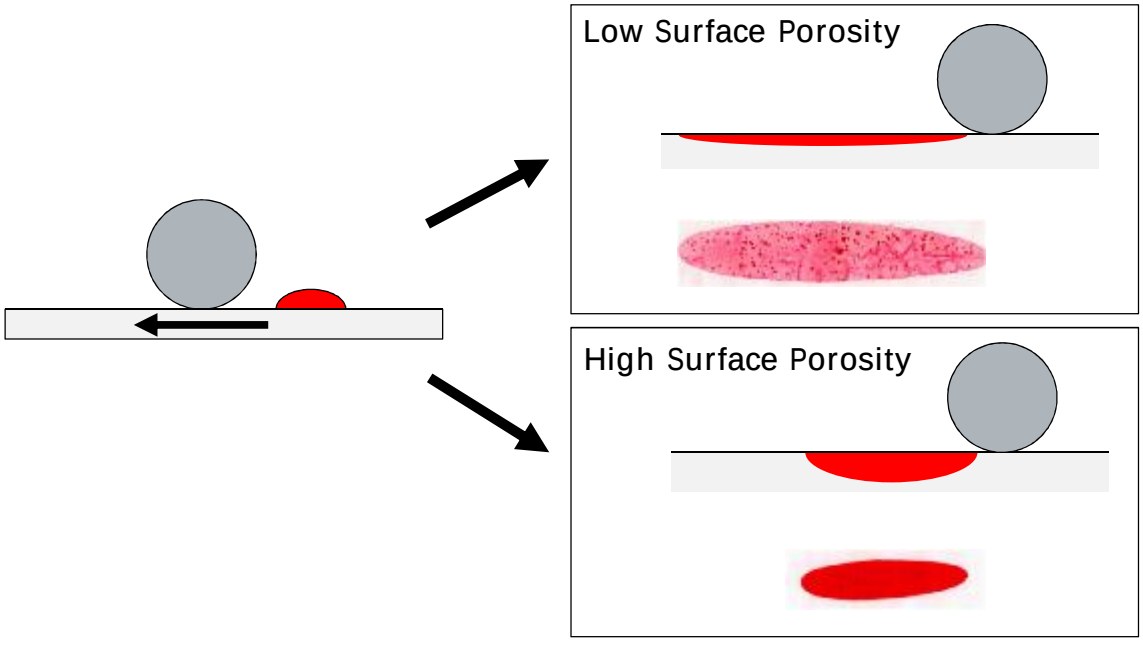
# Multilayer Coated Paper with Varying Topcoat Thickness



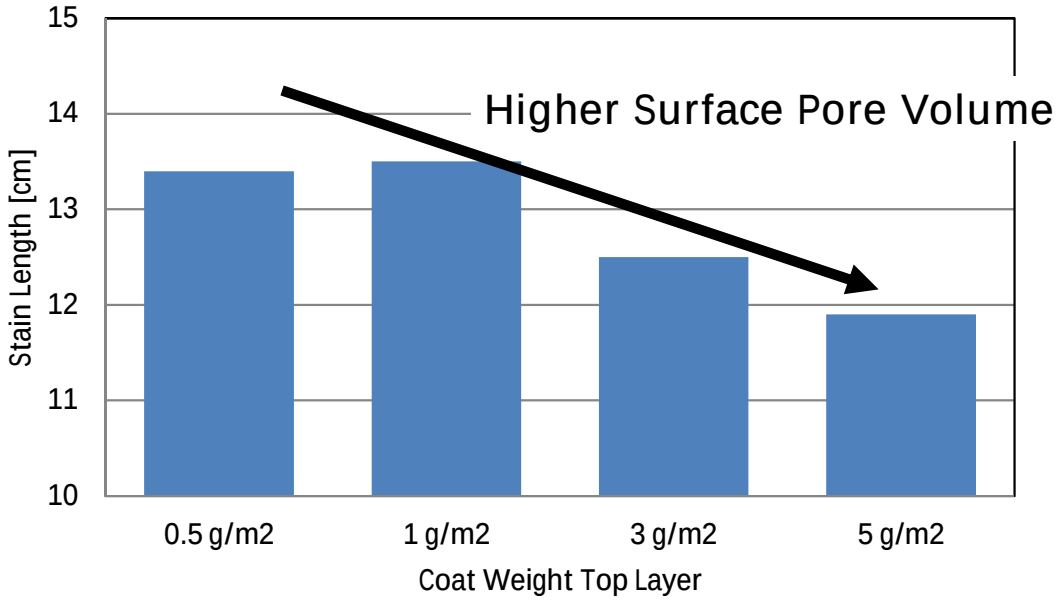





# Measurement of Surface Porosity - Print Penetration Test

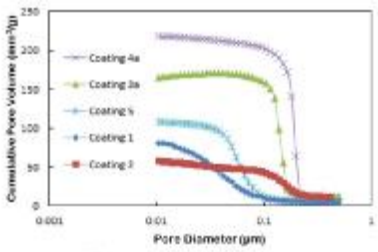


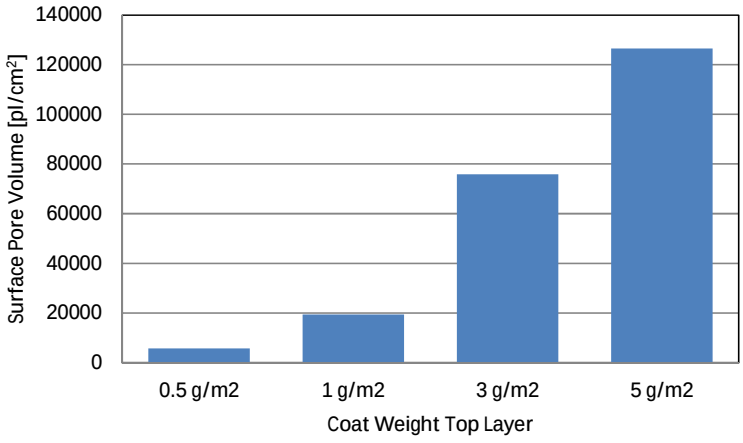
# Print Penetration Test





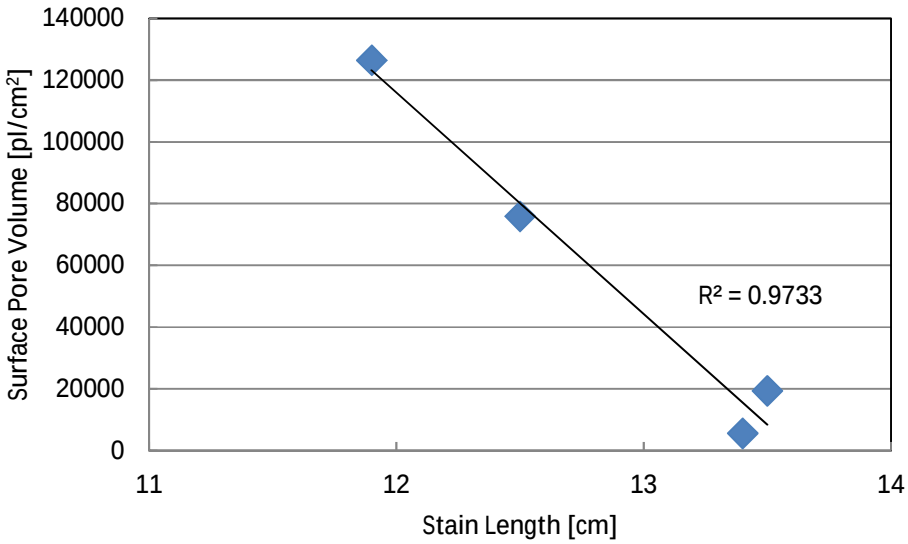

# Surface Pore Volume by Hg-porosimetry



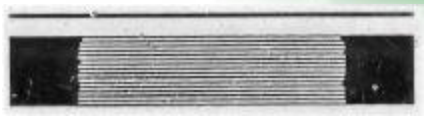

Porosity x [Coat Weight]

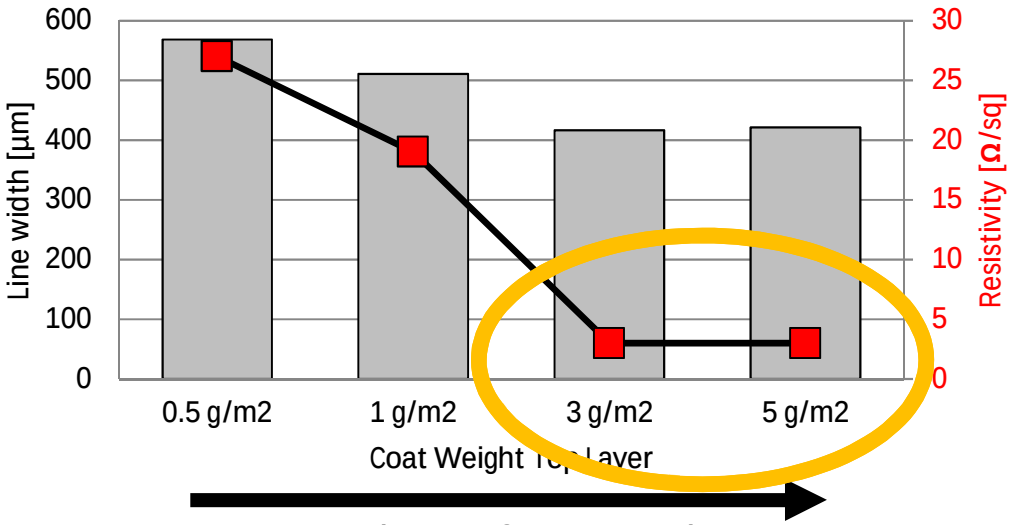
# Print Penetration vs. Hg-porosimetry





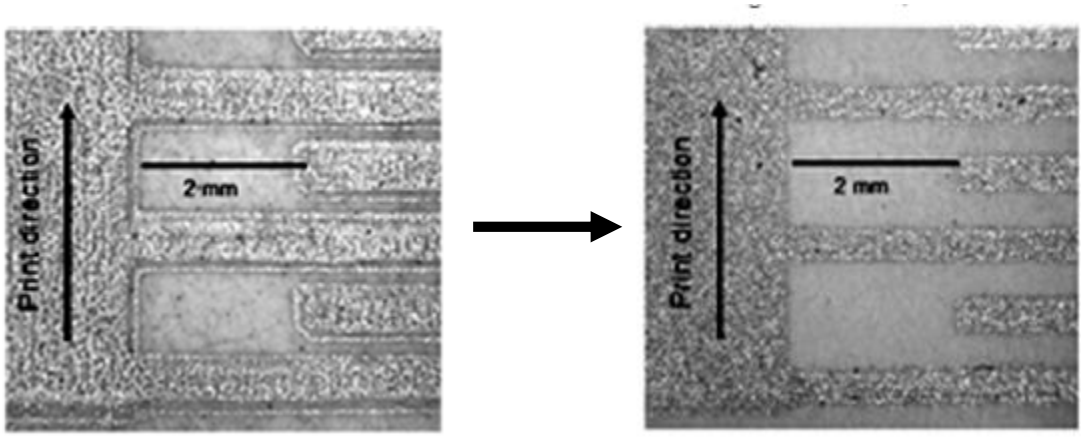

# Flexography & Silver Ink






- Increasing surface smoothness
- Increasing apparent surface energy
- Increasing surface pore volume

# Surface Porosity Minimizes Characteristic “Squeeze” in Flexography

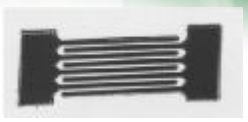


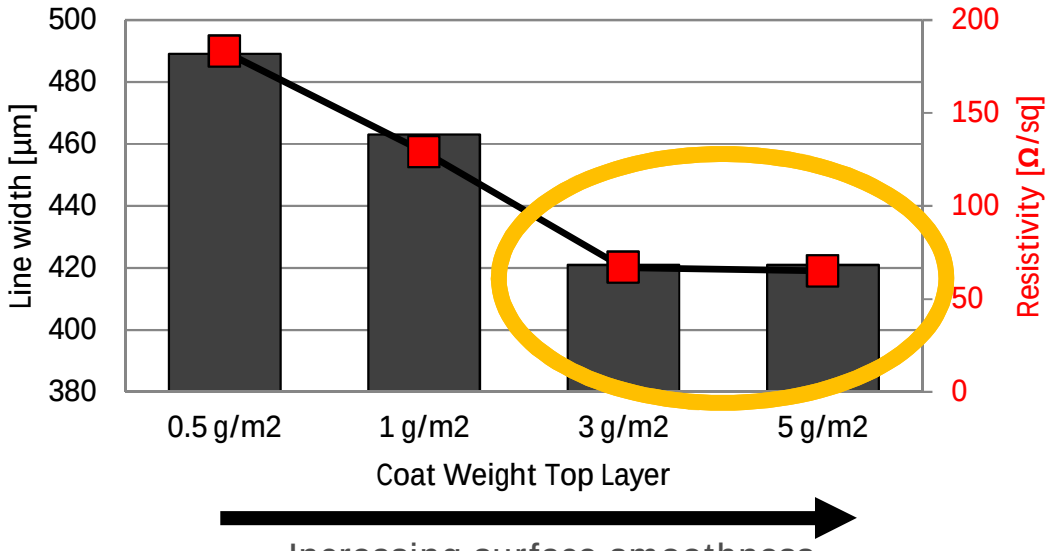

Low surface porosity

High surface porosity



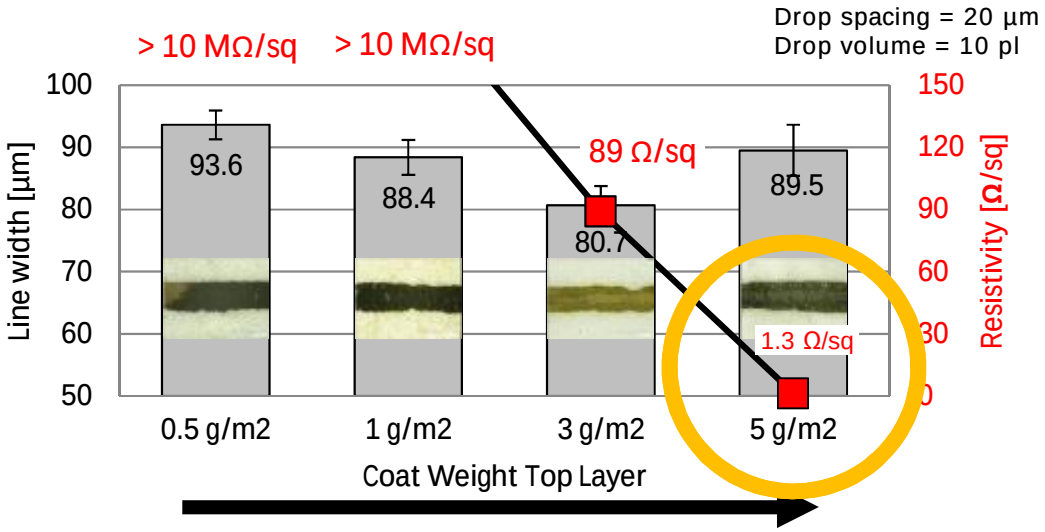
# Flexography & Carbon Ink






- Increasing surface smoothness
- Increasing apparent surface energy
- Increasing surface pore volume

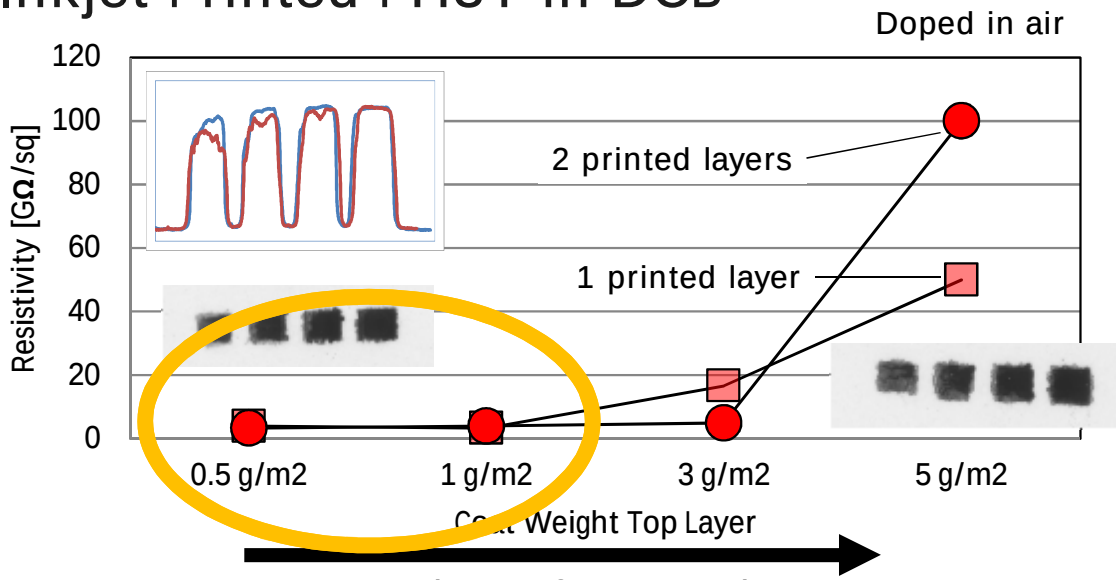
# Inkjet – Nanoparticle Silver Ink




- Increasing surface smoothness?
- Increasing apparent surface energy
- Increasing surface pore volume



# Inkjet Printed PH3T in DCB

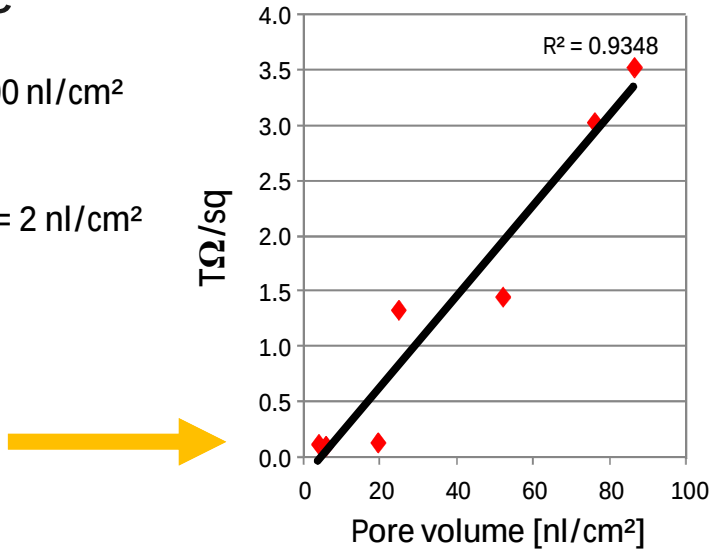



- Increasing surface smoothness
- Increasing apparent surface energy
- Increasing surface pore volume

# Surface Pore Volume vs. Semiconductor Performance

Total printed volume 800 nl/cm² at 0.25% **à**

P3HT volume on paper = 2 nl/cm²




**à** A thinner and less porous topcoat preferable

R. Bollström, D. Tobjörk, P. Dolietis, P. Salminen, J. Preston, R. Österbacka and M. Toivakka, Printability of functional inks on multilayer curtain coated paper, Chemical Engineering and Processing (Submitted)

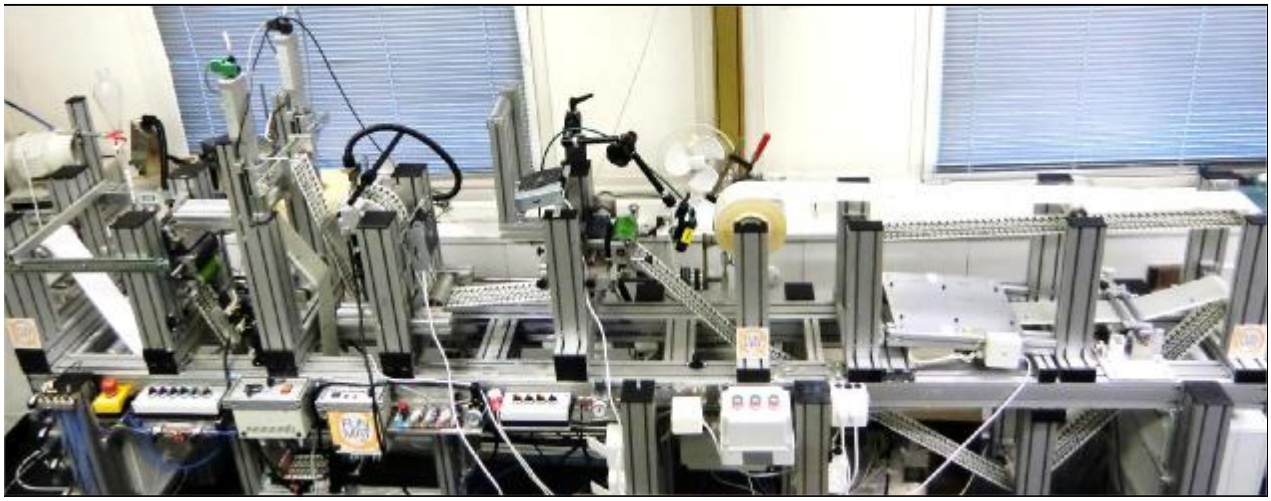


# Influence of Surface Pore Volume on Printability of Functional Inks

- Printability of particulate inks improves on porous surfaces (if particles > pore size):
  - › Less squeeze in flexography
  - › Less spreading in inkjet
  - › Coffee stain effect minimized
- Printability of dissolved functional inks improves on low porosity surfaces:
  - › Functionality is reduced due to penetration into the porous surface

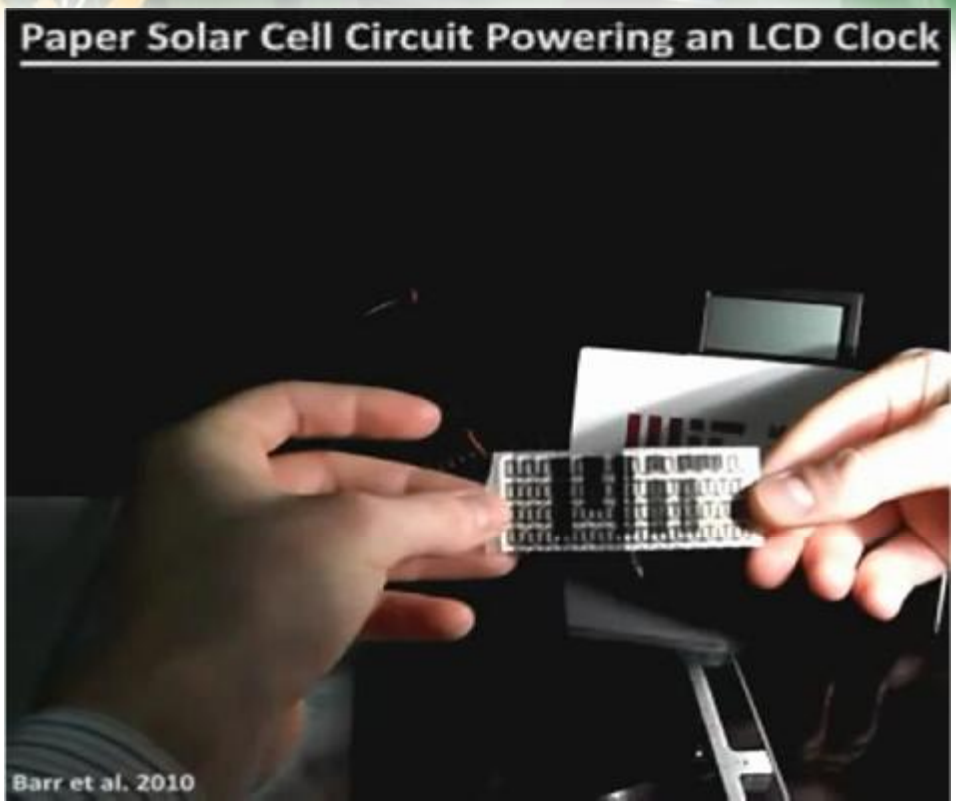
→ Compromise or new concepts (use other parameters)

# Roll-to-roll Production – FunPrinter



**à** Roger Bollström: High volume printing of devices and sensors on paper






Barr et al., *Direct Monolithic Integration of Organic Photovoltaic Circuits on Unmodified Paper,* Adv. Mat. 2011

# Future of Paper Electronics

- Paper as substrate for printed electronics is "different" from plastics – in "good" and "bad"
- FunMat has demonstrated printed transistors and other devices on paper
- Main challenges are non-existence of suitable hybrid printers, niche market position and market "resistance"
- First products will be simple sensors for biological, biomedical and chemical applications



# Recent Publications

http://www.funmat.fi/


- Bollström, R., M. Tuominen, A. Määttänen, J. Peltonen, and M. Toivakka. "Top layer coatability on barrier coatings." *Progress*
- Bollström *Measurement Science*
- Tobjörk, . Toivakka, H. Tenhu et al. "IR-sintering of ink-jet printed metal-nanoparticles on paper." *Thin Solid Films* 520, no. 7 (2012): 2949–2955.
- Ihalainen, P., A. Määttänen, U. Matti tka, J. Bobacka, and J. Peltonen. "Electrodeposition of PEDOT-Cl film ode." *Thin Solid Films* 519 (2011): 2172–2175.
- Saarinen, J. J., P. Ihalainen, A. Määtt nted sensor and electric field assisted wetting on a natural fibre based sub *Journal* 26, no. 1 (2011).
- Määttänen, A., D. Fors, S. Wang, D. "Paper-based planar reaction arrays for printed diagnostics." *Sensors and A* 1404–1412.
- Määttänen, A., P. Ihalainen, R. Bolls ting and print quality study of an inkjet-printed poly(3-hexylthiophene) on *urfaces A: Physicochemical and Engineering Aspects* 367, no. 1-3 (2010): 76–84
- Määttänen, A., P. Ihalainen, R. Bolls nen. "Enhanced Surface Wetting of Pigment Coated Paper by UVC Irradiation." *In rch* 49, no. 22 (2010): 11351–11356.
- Pykönen, M., K. Johansson, R. Bollst ence of Surface Chemical Composition on UV-Varnish Absorption into Permea *Engineering Chemistry Research* 49, no. 5 (2010): 2169–2175.
- Bollström, R., A. Määttänen, D. Tobjörk, P. Ihalainen, N. Kaihovirta, R. Österbacka, J. Peltonen, and M. Toivakka. "A multilayer coated fiber-based substrate suitable for printed functionality." *Organic Electronics* 10, no. 5 (2009): 1020–1023.